BELLCOMM, INC.

SUBJECT: Oxygen Enrichment of the CM Atmosphere from On-board Supplies Case 330
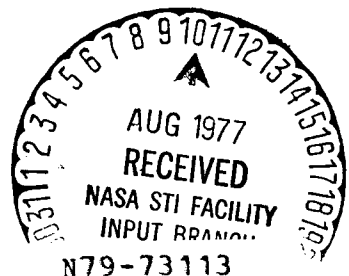
DATE: August 15, 1967

FROM: L. G. Miller

ABSTRACT

If air (or enriched air) is used to pressurize the Apollo CM on the pad, the ambient atmosphere must be replaced or enriched to a physiologically safe level before the crew can remove their suits. For a selection of initial conditions which is thought to reasonably bracket the possible alternatives, this memorandum

1. determines the time-flow rate requirements for oxygen enrichment to satisfy an assumed set of crew physiological requirements,

2. illustrates the relative penalty of using the various enrichment procedures, and

3. compares these results to the requirements of a proposed set of design criteria.

It is concluded for the cases examined that, even with a generous (i.e. 7.4 lbs) on-board supply of readily available gaseous oxygen, a cabin atmosphere transition to 95% oxygen can only be attained by venting the cabin to vacuum and repressurizing with pure oxygen. Other procedures required as much as <u>three</u> or <u>four</u> times the available supply to attain the same end point. In addition, all of the atmosphere transition procedures would compromise the capability for maintaining survival levels of atmosphere in the event of a micrometeroid puncture for varying periods of time.

BELLCOMM, INC.

MEMORANDUM FOR FILE

      This memorandum examines the posture resulting from a manned Apollo launch with air (or enriched air) in the CM cabin. If air is used to pressurize the spacecraft on the pad, the ambient atmosphere must be replaced or enriched to a physiologically safe level before the crew can remove their suits. For a selection of initial conditions and enrichment procedures, this memorandum

1. determines the time-flow rate requirements for oxygen enrichment to satisfy an assumed set of crew physiological requirements,

2. illustrates the relative penalty of using the various enrichment procedures, and

3. compares these results to the requirements of a proposed set of design criteria.

Results of the study are interpreted in light of physiological requirements for partial pressure of oxygen as related to cabin pressure[1].

      The following CSM Environmental Control System design criteria are proposed[2]:

1. If air is used as the CSM pressurant during countdown and ascent to orbit, the system shall demonstrate the capability of supporting crew physiological requirements of respiration and pressure in the event of a suit-loop failure.

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[1]Physiological Constraints for Air-on-the Pad, Case 330, by T. A. Bottomley, Jr. dated August 31, 1967.

[2]Functional Requirements and Time Line Constraints for Cabin Atmosphere Evaluation, Apollo Saturn V, Case 330, by R. D. Raymond dated August 31, 1967.

2. If air is used as the CSM pressurant during
    countdown, the system shall be capable of
    exchanging the initial CSM atmosphere for
    pure oxygen as soon as practicable after
    reaching initial flight pressure and prior
    to initial doffing of suits.

3. The capability for maintaining survival levels
    of atmosphere in the event of micrometeroid
    puncture shall be retained throughout the
    mission.

The reference of footnote 2 describes the CM pressure history
for a nominal ascent to parking orbit which has been used as
a basis for the present study. It presents a number of
alternatives for atmosphere control which are evaluated herein.

PROBLEM DEFINITION

      With respect to physiological considerations and
minimizing the requirement for on-board oxygen supplies, it is
desirable that pure oxygen be used for a CM cabin atmosphere
following spacecraft closeout. This assumes the existence of
satisfactory provisions for fire prevention and extinguishment.
However, if such provisions are not satisfactory, it is con-
ceivable that air or air enriched with oxygen may be specified
for use in the CM during launch-pad operations. The problem
then becomes one of determining how and when to attain the
desired spacecraft atmosphere for subsequent mission phases
at the least cost.

      There are a number of constraints on any solution
to this problem. For example, one certainly wants to minimize
the risk of decompression sickness or hypoxia. One would also
want to minimize the fire hazard or at least provide an
atmosphere which is no more hazardous than pure oxygen at
5 psia. One might also wish to specify a lower bound on total
cabin pressure or an upper bound on the time of attainment of
a safe oxygen atmosphere in the CM cabin. The design criteria
from the previous section must also be considered.

      This memorandum does not attempt to establish the
relative fire hazards of the many possible solutions nor does
it purport to establish physiologically safe levels for the
partial pressure of oxygen. Rather, a parametric study has
been made using values which are thought to reasonably bracket
the possible alternatives. The initial conditions and enrich-
ment procedures which have been examined are listed below.
Letters corresponding to specific cases are used in the
identification of curves on figures contained herein.

Procedure	CM Atmosphere at Launch	Enrichment Procedures
A	Air	Constant flow rate starting at lift-off
B	Air	Constant flow rate starting at T greater than or equal to 120 seconds
C	Air enriched to 33% oxygen	Constant flow rate starting at T greater than or equal to 120 seconds
D	Air	Constant flow rate starting between T-0 and T+95 seconds[3]
E	Air enriched to 30% oxygen	Constant flow rate starting between T-0 and T+95 seconds[3]
F	Air enriched to 40% oxygen	Constant flow rate starting between T-0 and T+95 seconds[3]
G	Air enriched to 67% oxygen	Constant flow rate starting at T greater than or equal to 120 seconds
H	Air	Cycles consisting of depressurization to 3 psia and repressurization (with oxygen at constant flow rates) to 5 psia starting at T greater than or equal to 120 seconds
I	Air	One cycle consisting of depressurization to 0 psia and repressurization to 5 psia (at constant flow rate) starting at T greater than or equal to 120 seconds

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[3]These special cases were used to define flow rates and oxygen requirements for a specific final condition. Details will be discussed in a later section of this memorandum.

CALCULATIONS AND ASSUMPTIONS

The method of calculation for this study borrows heavily from two previous works[4, 5]. In the interest of completeness, the pertinent assumptions are listed below:

1. Calculations are based on a Block II command module with a free volume of 306 cubic feet. Venting during ascent is assumed to take place through both sides of the cabin pressure relief valve corresponding to a total geometrical area of 3.53 sq. in. The orifice coefficient, which varies between .63 and .85, is assumed to be a linear function of the pressure ratio.

2. Depressurization and repressurization are assumed to take place isothermally at a cabin temperature of 75°F. It is further assumed that mixing of the gases is perfect and instantaneous. Dalton's Law is used to develop partial pressures, and Gibb's Law is used to calculate the physical properties of the mixture of gases.

3. For purposes of comparison, it is assumed that 7.4 pounds[6] of gaseous oxygen will be available for atmosphere enrichment. No limitations on mass flow rate have been established.

4. For those cases requiring depressurization, it is assumed that one side of the cabin pressure relief valve is used corresponding to a total geometric area of approximately 1.76 sq. in.

5. The crew availability time constraint has not been considered. That is, it is assumed that the necessary operations could be accomplished without interfering with other crew tasks.

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[4] "Final Report: Command Module Depressurization During Terminal Countdown - Case 330," Memorandum For File, by L. G. Miller, dated January 20, 1967.

[5] "A Parametric Study on the Use of Diluent Gases as a Means of Extinguishing Spacecraft Fires in Flight," TM 67-2032-1, Case 330, by L. G. Miller, dated April 17, 1967.

[6] This number is twice the capacity of the old Bk I ECS surge tank. The effect of using a smaller oxygen supply will be mentioned in a later section of this memorandum.

For the nominal ascent, it is assumed that the CM pressure remains at its initial level until the external ambient pressure corresponds to a 6 psi differential. From that point, the computer has been programmed to maintain a maximum positive differential of 6 psi with respect to ambient pressure. When the external ambient pressure reaches zero, the computer is programmed to decrease the cabin pressure at · a rate corresponding to normal leakage and metabolic use. (A rough calculation indicates that this bleed-down process from 6 to 5 psia may take on the order of four hours.) This pressure decay does not begin immediately when enrichment is accomplished using procedures A through G. Since they depend on a constant flow of oxygen to achieve atmosphere transition, the cabin pressure remains at a level corresponding to the opening pressure of the cabin pressure relief valve (i.e. 6 psia). Repressurization is to 5 psia for H and I, hence leakage plays an insignificant role in those cases.

Ascent conditions are based on Design Reference Mission II A (MSC Report No. PM3/M-171/66 dated 30 October 1966). The computer program uses this information to calculate the value of oxygen partial pressure, nitrogen partial pressure, and total cabin pressure at intervals of one second. The various enrichment procedures are superimposed on this process.

RESULTS

With a small amount of interpretation, all of the cases set forth under the section on Problem Definition can be compared using Figures 1, 2 and 3. Figure 1 illustrates the relationship between gaseous oxygen flow rate and the minimum time required to reach an arbitrary end point (95% oxygen in this case) for the cases identified as A, B, C, G, H and I. For the same cases, Figure 2 illustrates the relationship between oxygen flow rate and the amount of oxygen required to reach the selected end point. Figure 3 is more specific in that the end point is specified in terms of both time and percentage of oxygen. In this case, the abscissa represents the time after launch at which oxygen enrichment commences.

In Figure 1, the curves are plotted on different axes primarily for clarity. The shaded portions on the top two sets of axes bound the capabilities of the assumed on-board oxygen stores. It is immediately obvious that none of these modes are capable of attaining a 95% oxygen atmosphere within the indicated time frame if the available supply of gaseous oxygen is limited to 7.4 pounds. Matters are somewhat better when, as in Procedures B, C and G, enrichment starts
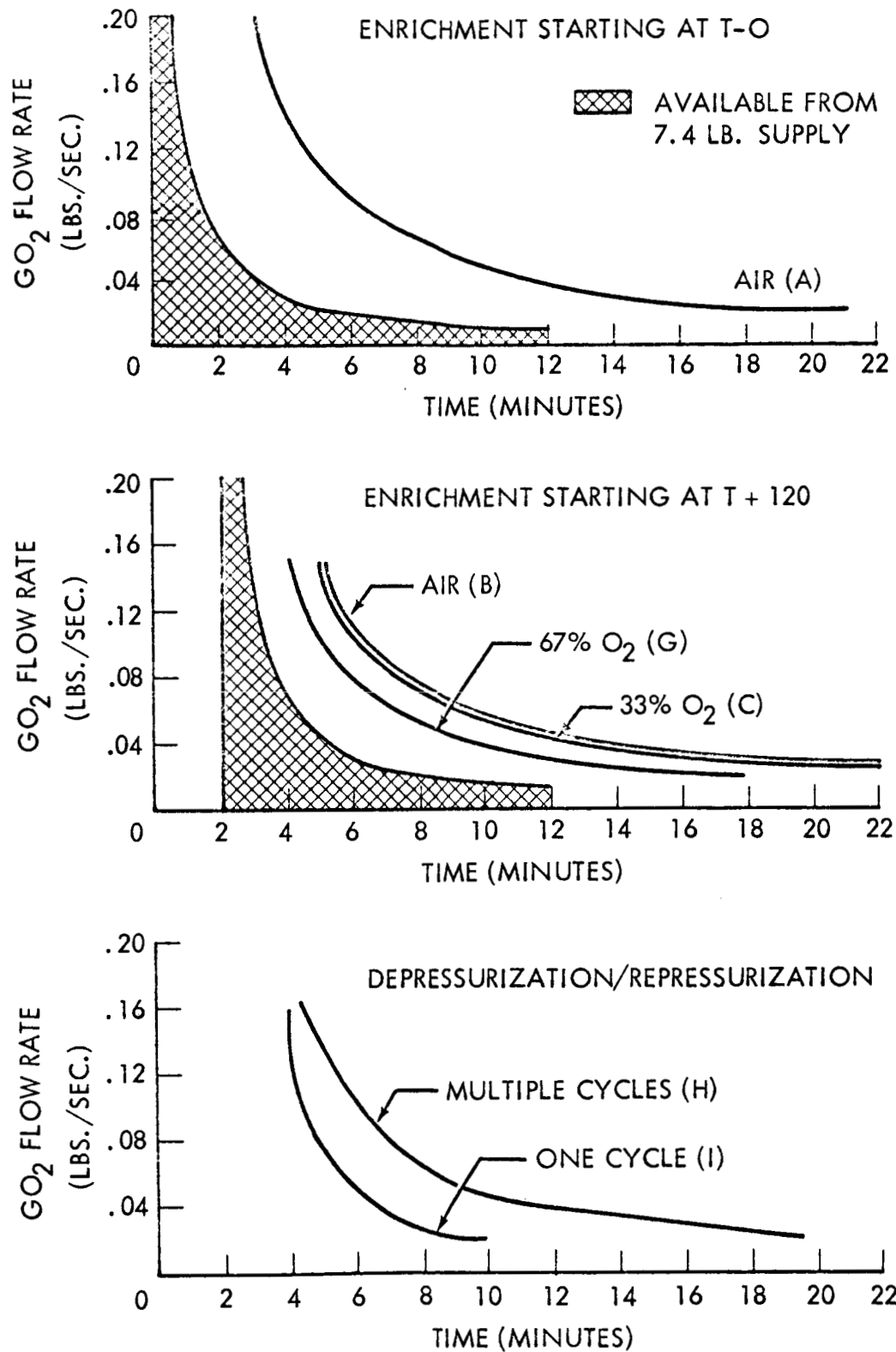
FIGURE 1: TIME REQUIRED TO REACH 95% O_2 IN CM CABIN AS A FUNCTION OF GO_2 FLOW RATE FOR DIFFERENT MODES
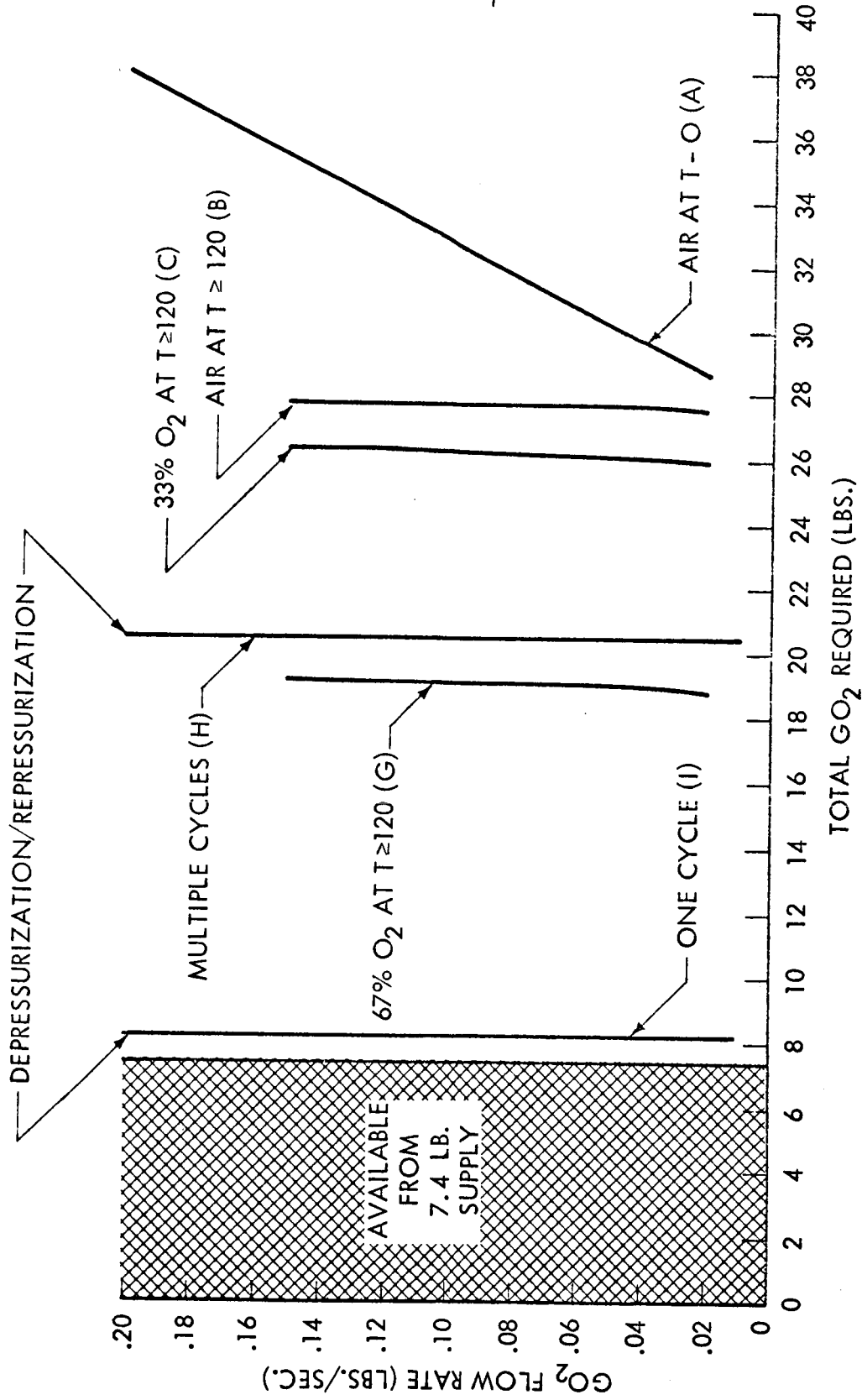
FIGURE 2: AMOUNT OF GO$_2$ REQUIRED TO YIELD 95% O$_2$ IN CM CABIN AS A FUNCTION OF O$_2$ FLOW RATE FOR DIFFERENT MODES.
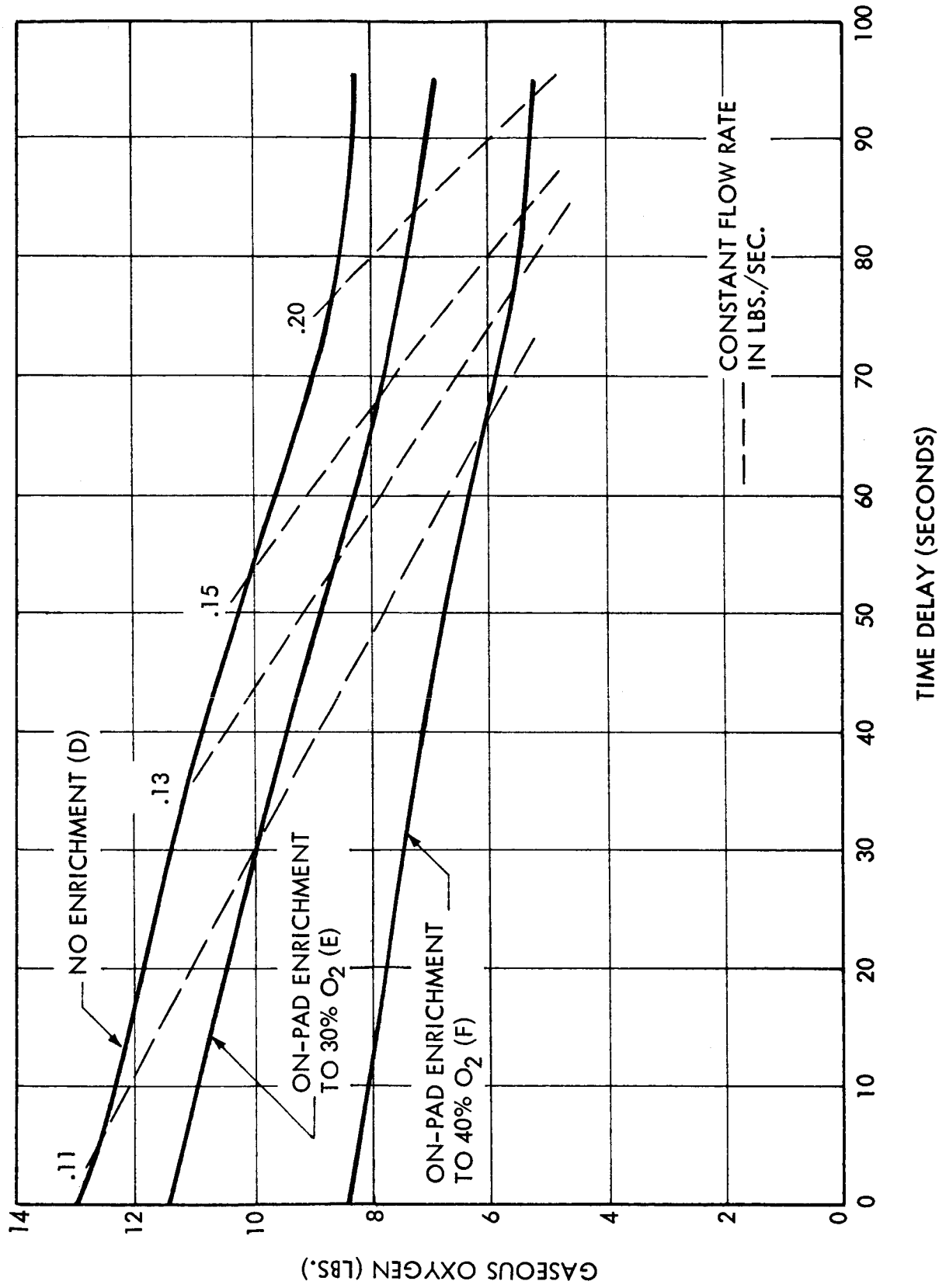
FIGURE 3: AMOUNT OF GASEOUS OXYGEN REQUIRED TO REACH 63% O₂ IN CM CABIN AFTER 120 SECONDS OF FLIGHT AS A FUNCTION OF DELAY IN INITIATING OXYGEN FLOW.

at T+120 seconds, but Figure 2 shows that there is no great improvement in the amount of oxygen required from on-board supplies unless one uses the method of Procedure I or a high level of on-pad enrichment.

It is interesting to note that, with the exception of the one-cycle depressurization and repressurization of Procedure I, the times required to reach the end point are grouped fairly closely for any given flow rate. Thus, generally, one does not have to consider a time trade-off in evaluating the desirability of the procedures covered in this paper unless low flow rates (i.e. less than .03 lb./sec.) are used.

The depressurization/repressurization cases (i.e. H and I) are representative of proposals which have been suggested by a number of sources[7]. Given that something fairly well removed from pure oxygen is used as a cabin atmosphere at launch, the one-cycle depressurization of Procedure I is by far the most efficient method of performing the post-launch atmosphere transition. In light of presently known plans[8] for rapid CM repressurization, it also appears to be the fastest means of attaining the flight atmosphere. The procedure using multiple cycles results in a "sawtooth" pressure profile. It requires more than twice the oxygen of Procedure I but does not require depressurization to a vacuum. For the case shown, six cycles were required to reach the 95% end point.

One feature in the labeling of Figure 1 should be noted. The cases identified as "Enrichment Starting at T+120" are referred to as "enrichment starting at T greater than or equal to 120 seconds" in both the text and in Figure 2. The actual calculations for those cases were initiated at T+120 seconds, but the external ambient pressure at that time is close enough to zero to permit the assumption that the calculation is valid for all times greater than T+120 seconds. That is, venting during ascent is essentially complete, and the character of the flow is determined by

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[7]NASA Apollo Program Working Paper No. 1251-A, O&E Addendum A, MSC, Houston, Texas, April 5, 1967, and private discussions with A. R. Nagy of the Aerospace Corporation, El Segundo, California.

[8]A repressurization profile which would yield 3 psia in one minute and 5 psia in about 30 minutes is being implemented (CCA 1315 to NAA).

the pressure ratio[9]. Since the pressure ratio will always be
less than the critical pressure ratio after 120 seconds, the
velocity of the fluid through the cabin pressure relief valve
will be sonic, and the mass flow will depend only upon the
parameters of the fluid and of the reservoir (i.e. the cabin).
Thus, the process becomes predictable, and one can "slide"
the curves forward in time with little loss of accuracy.

The relative advantage of the various procedures
with respect to gaseous oxygen requirements is clearly illus-
trated in Figure 2. With the exception of the case where
enrichment starts at T-0, the data shows an almost negligible
dependence on flow rate. The variation in total gaseous
oxygen requirements for the different procedures, however,
is quite striking. If readily available on-board stores are
limited to 7.4 pounds, one cannot attain a 95% oxygen atmos-
phere in the CM cabin (for the cases covered herein) without
drawing on the normal CM oxygen supply. The case is that
much stronger when on-board stores are smaller than the
assumed value. If this total oxygen flow rate from the SM
is limited to approximately 8.2 lbs/hr., one can gain some
idea of the timing associated with the various procedures.

Take, as an example, the case of oxygen enrichment
at a constant rate starting at some T greater than 120 seconds
with air initially in the CM cabin (i.e. Procedure B).
Figure 2 indicates that approximately 27.5 pounds of gaseous
oxygen are required to reach the 95% O_2 level. Once the on-
board stores were used, approximately 20 pounds of gaseous
oxygen would be required from the SM supplies. This would
take on the order of two hours. As a matter of interest,
another rough calculation indicates that this total SM flow
rate would have to be maintained for an additional 4-5 hours
before one reached a CM oxygen level of 99.9%.

Having gained some insight into the behavior of
these enrichment procedures, a more definitive problem was
taken on. Based on the reference of footnote 1, one can
work with the assumption that the CM cabin should contain
approximately 63% oxygen (at 6 psia) to assure acceptable
performance from personnel exposed to the cabin environment.
From the reference of footnote 1, it is noted that Mode IA
and IB aborts are not atmosphere critical. The Mode IC abort,
which is possible between T+90 and T+185 seconds, is atmos-
phere.critical after T+120 seconds. On this basis, a
number of enrichment procedures were performed which would
yield the 63% oxygen content at T+120 seconds. The results
are shown in Figure 3.

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[9]c.f. Appendix A of the reference of footnote 4. Pressure
ratio is defined as P_o/P where P is the cabin pressure and
P_o is the pressure outside of the spacecraft.

For three cases, which are thought to represent a reasonable spread of on-pad enrichment values, the computer was instructed to calculate the amount of gaseous oxygen from on-board stores which would yield the desired environment at T=120 seconds. The time at which enrichment was initiated is the independent variable. Lines of constant flow rate are shown to illustrate their relation to the enrichment procedure.
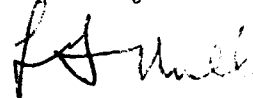
Figure 3 makes two significant points. First, some on-pad enrichment will be necessary in order to meet the oxygen requirement for a Mode IC abort if it is assumed that a suit loop failure has occurred which necessitates crew exposure to the cabin atmosphere. Secondly, there is an advantage to be gained in delaying the initiation of oxygen flow. For an 80 second delay, the savings of on-board oxygen amount to in excess of 50% when compared to the case where flow is initiated at T=0. The combination of some on-pad enrichment and delay in initiating oxygen flow will yield a viable cabin atmosphere for the Mode IC abort without exceeding the assumed on-board oxygen storage capacity.

CONCLUSIONS

Compared to the use of 100% oxygen, launch with a two-gas atmosphere yields a lower fire hazard during the first few minutes of flight, but this strategy requires complete reliance on the space-suit system to provide for the physiological needs of the crew. Additionally, it requires a post-launch atmosphere transition involving potential physiological, operational, and system penalties. This memorandum has presented a basis for comparing a number of atmosphere transition procedures in terms of gross system penalties. With a 7.4 lb on-board supply of readily available gaseous oxygen, a cabin atmosphere approaching 95% oxygen can only be attained by venting the cabin to vacuum and repressurizing with pure oxygen.

It is also important to note that all of the atmosphere transition procedures contemplate use of the 7.4 lb. supply and, therefore, would compromise the capability for maintaining survival levels of atmosphere in the event of micrometeroid puncture. The length of time that this condition would exist is directly related to the specification of a desired cabin environment at a given mission time. For example, it takes something in excess of 35 lbs of gaseous oxygen to go from 95% to 99.9% O_2 in the CM cabin if the

oxygen is just bled in. Thus, protection against loss of pressure could be restored more than four hours sooner (not to mention the savings in oxygen) if the mission were allowed to proceed with only 95% oxygen in the cabin.

On pursuing this strategy of obtaining a lower percentage of oxygen, one eventually comes up against a physiological limit for acceptable performance. Using 63% as the minimum oxygen percentage at initial flight pressure, this study has shown that some on-pad enrichment of the cabin atmosphere is necessary in order to attain that level in a timely manner. Again, however, the oxygen reserve for use in the event of a micrometeroid puncture would be all but exhausted unless higher levels of on-pad enrichment were used. The reader is also cautioned that the 63% oxygen level is thought to be inadequate when personnel are subjected to high acceleration loads. If, as proposed in the reference of footnote 1, an oxygen level of 95% is required some 200 seconds after initiation of abort, an abort initiated at T+120 seconds would require a four-fold increase in the assumed on-board oxygen storage capacity.

2032-LGM-gmp   L. G. Miller

BELLCOMM, INC.

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Atmosphere from On-board Supplies
Case 330

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